

New generation of double beta decay experiments: are there any limitations?

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Abstract. New generation experiments on search for neutrinoless double beta decay with sensitivity to effective Majorana neutrino mass on the level $\sim 3\text{-}5$ meV is discussed. Possible restrictions at achievement of this purpose (possibility to produce big amount of enriched isotopes, possibility to reach very low background level, energy resolution and possible cost of experiments) are considered. It is shown that for realization of so ambitious project 10 tons (or more) of enriched isotope is required. Background index should be on the level $\leq 10^{-5}\text{-}10^{-6}$ c/kg \cdot keV \cdot y. Besides, the energy resolution of the detector should be not worse than 1-2%. It is shown that $^{130}\text{TeO}_2$ low temperature bolometer looks as the most realistic candidate for such experiments. Under some conditions experiments with ^{76}Ge , ^{100}Mo and ^{136}Xe can be realized too.

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INTRODUCTION

The $0\nu\beta\beta$ -decay rate depends on the type of neutrino mass spectrum which can be hierarchical, with partial hierarchy or quasi-degenerate (see, e.g., [1]). Using the data on the neutrino oscillation parameters it is possible to show (see, e.g., [2]) that in the case of normal hierarchical spectrum one has $|\langle m_\nu \rangle| < 0.005\text{eV}$, while if the spectrum is with inverted hierarchy, $0.01\text{ eV} < |\langle m_\nu \rangle| < 0.05\text{ eV}$. A larger value of $|\langle m_\nu \rangle|$ is possible if the light neutrino mass spectrum is with partial hierarchy or of quasi-degenerate type. In the latter case $|\langle m_\nu \rangle|$ can be close to the existing upper limits. In the present work a current state of experiments on search for double beta decay (with sensitivity to $|\langle m_\nu \rangle| \sim 0.2\text{-}1\text{ eV}$) is analysed, offers on immediate prospects ($|\langle m_\nu \rangle| \sim 10\text{-}100\text{ meV}$) is considered and possibility to achieve the sensitivity $\sim 1\text{-}5\text{ meV}$ is estimated.

PRESENT STATUS

The constraints on the existence of $0\nu\beta\beta$ -decay are presented in Table 1 for the nuclei for which the best sensitivity has been reached. In calculating constraints on $|\langle m_\nu \rangle|$, the nuclear matrix elements (NMEs) from [12, 13, 14, 15, 16, 17] were used (3-d column). In column four, limits on $|\langle m_\nu \rangle|$, which were obtained using the NMEs from a recent Shell Model (SM) calculations [18] are presented (for ^{116}Cd NME from [19] is used). And now the limits on $|\langle m_\nu \rangle|$ for ^{130}Te and ^{100}Mo are comparable with the ^{76}Ge results. The assemblage of sensitive experiments for different nuclei permits one to increase the reliability of the limit on $|\langle m_\nu \rangle|$. Present conservative limit can be set as 0.75 eV .

In Table 2 the reached level of background in the mentioned above experiments is presented. Background index (BI) and sum background (ΣB) in region of interest (ROI) are given. One can see that BI in present experiments is quite high and one has a deal with background in ROI (there is no any "zero" background experiment up to now).

TABLE 1. Best present results on $2\beta(0\nu)$ decay (limits at 90% C.L.). *) See discussions in [6]; **) NME from [19] is used; ***) conservative limit from [10] is presented

Isotope	$T_{1/2}$, y	$ \langle m_\nu \rangle $, eV [12, 13, 14, 15, 16, 17]	$ \langle m_\nu \rangle $, eV [18]	Experiment
^{76}Ge	$> 1.9 \cdot 10^{25}$	$< 0.22 - 0.41$	< 0.69	HM [3]
	$\simeq 1.2 \cdot 10^{25}(?)^*)$	$\simeq 0.28 - 0.52(?)^*)$	$\simeq 0.87(?)^*)$	Part of HM [4]
	$\simeq 2.2 \cdot 10^{25}(?)^*)$	$\simeq 0.21 - 0.38(?)^*)$	$\simeq 0.64(?)^*)$	Part of HM [5]
	$> 1.6 \cdot 10^{25}$	$< 0.24 - 0.44$	< 0.75	IGEX [7]
^{130}Te	$> 2.8 \cdot 10^{24}$	$< 0.29 - 0.59$	< 0.77	CUORICINO [8]
^{100}Mo	$> 1.1 \cdot 10^{24}$	$< 0.29 - 0.93$	—	NEMO-3 [9]
^{136}Xe	$> 4.5 \cdot 10^{23}***)$	$< 1.41 - 2.67$	< 2.2	DAMA [10]
^{82}Se	$> 3.6 \cdot 10^{23}$	$< 1.89 - 1.61$	< 2.3	NEMO-3 [9]
^{116}Cd	$> 1.7 \cdot 10^{23}$	$< 1.45 - 2.76$	$< 1.8^{**})$	SOLOTVINO [11]

TABLE 2. Background index (BI) and sum background in ROI (ΣB) in the best present experiments. M- mass of investigated isotope, t - measurement time, Q - energy of 2β -decay, $\Delta E/E$ - energy resolution (FWHM). *) After pulse shape analysis; **) for ^{130}Te .

Experiment	M·t, kg·y	$\Delta E/E$, % at Q	BI, c/kg·keV·y	ΣB (ROI= ΔE)
HM	71	0.2	0.17 (0.02) ^{*)}	$\sim 50 (\sim 3)^*)$
IGEX	7	0.2	0.2 (0.06) ^{*)}	$\sim 7 (\sim 2)^*)$
CUORICINO	72 (20) ^{**))}	0.3	0.18	~ 70
NEMO-3 (^{100}Mo)	31	8	$1.4 \cdot 10^{-3}$	~ 18
DAMA	6.5	20	0.08	~ 250
SOLOTVINO	0.53	9	0.04	~ 5

NEXT GENERATION OF DOUBLE BETA DECAY EXPERIMENTS ($|\langle m_\nu \rangle| \sim 10\text{-}100 \text{ MEV}$)

There are a few tens of different propositions for future double beta decay experiments. Here seven of the most developed and promising experiments which can be realized within the next few years are presented (see Table 3). The estimation of the sensitivity in the experiments is made using NMEs from [12, 13, 14, 15, 16, 17, 18]. In all probability, they will make it possible to reach the sensitivity for the neutrino mass at a level of 0.01 to 0.1 eV. In Table 4 planned BI and ΣB in ROI are presented. For BI we are waiting for 100-1000 times lower values in comparison with present experiments. And even under such improvements ΣB will be non-zero. But in some cases (MAJORANA, EXO, SuperNEMO) it will be just a few events after 5-10 years of measurements.

TABLE 3. Seven most developed and promising projects. Sensitivity at 90% C.L. for three (1-st step of GERDA and MAJORANA, SNO+, and KamLAND-Xe) five (EXO, SuperNEMO and CUORE) and ten (full-scale GERDA and MAJORANA) years of measurements is presented. M - mass of isotopes.

Experiment	Isotope	M, kg	Sensitivity $T_{1/2}$, y	Sensitivity $ \langle m_\nu \rangle $, meV	Status
CUORE [20]	^{130}Te	200	2.1×10^{26}	35–90	in progress
GERDA [21]	^{76}Ge	40	2×10^{26}	70–300	in progress
		1000	6×10^{27}	10–40	R&D
MAJORANA [22, 23]	^{76}Ge	30–60	$(1-2) \times 10^{26}$	70–300	in progress
		1000	6×10^{27}	10–40	R&D
EXO [24]	^{136}Xe	200	6.4×10^{25}	95–220	in progress
		1000	8×10^{26}	27–63	R&D
SuperNEMO [25, 26, 27]	^{82}Se	100–200	$(1-2) \times 10^{26}$	40–110	R&D
KamLAND-Xe [28]	^{136}Xe	400	4.5×10^{26}	40–80	in progress
		1000	$\sim 10^{27}$	25–50	R&D
SNO+ [29]	^{150}Nd	56	$\sim 4.5 \times 10^{24}$	100–300	in progress
		500	$\sim 3 \times 10^{25}$	40–120	R&D

TABLE 4. Background index (BI) and sum background in ROI (ΣB) in the next generation experiments. M-mass of isotope, Q - energy of 2β -decay. ΣB is given for the measurement time indicated in Table 3. *) Full weight of the detector.

Experiment	Isotope	M, kg	$\Delta E/E$ at Q, %	BI, c/kg·keV·y	ΣB (ROI= ΔE)
CUORE	^{130}Te	200 (740)*)	0.3	0.01	~ 180
GERDA	^{76}Ge	40	0.16	0.001	~ 0.4
		1000	0.16	< 0.001	< 30
MAJORANA	^{76}Ge	30–60	0.16	0.001	$\sim 0.3-0.6$
		1000	0.16	0.00025	~ 8
EXO	^{136}Xe	200	3.8	0.001	~ 100
		1000	3.8	$\sim 2 \cdot 10^{-6}$	~ 1
SuperNEMO	^{82}Se	100–200	4–5	$\sim 2 \cdot 10^{-5}$	$\sim 1-2$
KamLAND-Xe	^{136}Xe	400 ($1.6 \cdot 10^4$)*)	10	$\sim 10^{-6}$	~ 15
		1000 ($4 \cdot 10^4$)*)			~ 40
SNO+	^{150}Nd	56 (10^6)*)	6.4	$\sim 10^{-6}$	~ 600
		500 (10^6)*)			~ 600

NEW GENERATION OF DOUBLE BETA DECAY EXPERIMENTS ($|\langle m_\nu \rangle| \sim 1-5$ MEV)

Table 5 presents number of nuclei in 10 tons of different isotopes and number of events obtained with 10 t of isotope after 10 y of measurement and for $T_{1/2} = 10^{29}$ y. In Table 6 estimated half-life values for different isotopes and for $|\langle m_\nu \rangle| = 1, 3$ and 5 meV are presented. In bold $T_{1/2}$ values at which disintegration can be registered are allocated. Using information from Tables 5 and 6 one can conclude that with 10 t of isotope sensitivity to $|\langle m_\nu \rangle|$ on the level 3–5 meV can be reached with some isotopes. The best

sensitivity can be reached with ^{100}Mo and ^{150}Nd . With ^{136}Xe it will be difficult to reach even 5 meV sensitivity. And for ^{48}Ca the best possible sensitivity is estimated as ~ 7 meV only.

TABLE 5. Number of nuclei in 10 t of isotope and number of events after 10 years of measurement (for $T_{1/2} = 10^{29}$ y).

Isotope	N of nuclei in 10 t of isotope	Events per 10 t and 10 y ($T_{1/2} = 10^{29}$ y)
^{48}Ca	$1.25 \cdot 10^{29}$	8.6
^{76}Ge	$7.9 \cdot 10^{28}$	5.5
^{82}Se	$7.3 \cdot 10^{28}$	5
^{100}Mo	$6 \cdot 10^{28}$	4.1
^{116}Cd	$5.2 \cdot 10^{28}$	3.6
^{130}Te	$4.6 \cdot 10^{28}$	3.2
^{136}Xe	$4.4 \cdot 10^{28}$	3
^{150}Nd	$4 \cdot 10^{28}$	2.8

TABLE 6. Half-life values (in yr) for different values of $|\langle m_\nu \rangle|$. NME values from [12, 13, 14, 15, 16, 17, 18] were used.

Isotope	$ \langle m_\nu \rangle = 1 \text{ meV}$	$ \langle m_\nu \rangle = 3 \text{ meV}$	$ \langle m_\nu \rangle = 5 \text{ meV}$
^{48}Ca	$1.1 \cdot 10^{31}$	$1.2 \cdot 10^{30}$	$4.4 \cdot 10^{29}$
^{76}Ge	$(0.9-9) \cdot 10^{30}$	$(0.1-1) \cdot 10^{30}$	$(0.37-3.6) \cdot 10^{29}$
^{82}Se	$(0.28-1.9) \cdot 10^{30}$	$(0.3-2.1) \cdot 10^{29}$	$(1.1-7.6) \cdot 10^{28}$
^{100}Mo	$(0.9-9.4) \cdot 10^{29}$	$(0.1-1) \cdot 10^{29}$	$(0.37-3.8) \cdot 10^{28}$
^{116}Cd	$(0.36-1.3) \cdot 10^{30}$	$(0.4-1.4) \cdot 10^{29}$	$(1.4-5.2) \cdot 10^{28}$
^{130}Te	$(0.24-1.7) \cdot 10^{30}$	$(0.27-1.9) \cdot 10^{29}$	$(1-6.8) \cdot 10^{28}$
^{136}Xe	$(0.89-3.2) \cdot 10^{30}$	$(1-3.6) \cdot 10^{29}$	$(0.36-1.4) \cdot 10^{29}$
^{150}Nd	$(1.2-4.2) \cdot 10^{29}$	$(1.3-4.7) \cdot 10^{28}$	$(0.48-1.7) \cdot 10^{28}$

Possible experimental approaches

Let's consider possible experimental approaches to such measurements:

- HPGe detectors;
- low temperature bolometers;
- liquid scintillator detectors (KamLAND, SNO+, SK+, BOREXINO);
- liquid (or gas) Xe detectors (EXO, XMASS, NEXT);
- new ideas - !?

Most of these approaches are used in present experiments (see reviews [6, 30]). And I hope that the new ideas are coming.

Possible background limitations

Background conditions are the key point for 2β -decay experiments. To detect the $0\nu\beta\beta$ -decay one has to detect (as minimum) ~ 5 -10 events and background has to be ~ 0 -2 events only! Say, for HPGe detectors BI has to be $< 5 \cdot 10^{-6} \text{ c/kg} \cdot \text{keV} \cdot \text{y}$ (\sim

100 times better than planned background in MAJORANA). Background will be a real problem for next generation experiments. Main sources of background are the following:

- contaminations in detector and shield;
- cosmic rays;
- 2ν tail;
- solar, reactor and geo neutrinos.

Of course, needed purity is different for different experiments. But, in any case, it is better to have "clever" detector, which can recognize 2β events (granularity, anticoincidence, tracks reconstruction, daughter ions registration and so on). It is well known that in BOREXINO, SNO, KamLAND purity of different liquids and gases is on the level $\sim 10^{-16}$ - 10^{-17} g/g of U and Th. In principle, solid material can be purified to the same level (in present experiments it is $\sim 10^{-12}$ g/g). So, in principle, one can have pure enough materials for 10 t 2β -decay experiments. But it will take a lot of efforts, time and money. Concerning to cosmic rays, main background is connected with muons itself, γ and neutrons induced by cosmic ray muons and radioactive isotopes produced by muons. Main recipe here is to go deep underground (6000 m w.e. or more) and to use effective veto shield. In Ref. [31] it was demonstrated that $BI = 10^{-6}$ c/keV \cdot kg \cdot y can be obtained for HPGe detectors. To avoid contribution from 2ν tail energy resolution has to be better than 1-2% (see discussion in [32]). Recently it was demonstrated that BI connected with solar neutrinos will be on the level $\sim (1-2) \times 10^{-7}$ c/keV \cdot kg \cdot y [33]. So, if energy resolution is good enough (say, 1-2%) this contribution will be negligible in most cases. Background from reactor and geo neutrino are in ~ 10 and ~ 100 times lower [34].

Possibilities of double beta isotope production

There are different methods for isotope production:

- centrifugation (productivity in arbitrary units is 1);
- laser separation (productivity is ~ 0.1);
- plasma separation (productivity is ~ 0.01);
- electromagnetic separation (productivity is ~ 0.001).

Taking into account the productivity and cost (which is proportional to productivity) it is clear that centrifugation is the only method to produce 10 tons of enriched material for 2β -decay experiments. Present productivity one can estimate as ~ 200 kg per year. It can be increased in ~ 10 times (with additional money investment). So, 10 t can be produced during 5-10 years. If it will be necessary new facility can be organized for this goal.

Cost of experiments

Some cost estimations are presented in Table 7. One can see that cheapest possibilities are ^{136}Xe and ^{130}Te . ^{76}Ge and ^{100}Mo are on the border of money possibilities. For other isotopes cost start to be real limitation. In case of ^{136}Xe there is another problem. Xenon is very rare material, its concentration in atmosphere is $\sim 10^{-5}\%$. World rate production

TABLE 7. Approximate price of 2β isotopes obtained by senrifugation. *) Taking into account 20% reduction for mass production case.

Isotope	Abundance	Price per kg, kS	Cost of 10 t, Mln.S
^{76}Ge	7.61	~ 80	800 (640)*)
^{82}Se	8.73	~ 120	1200 (1000)*)
^{100}Mo	9.63	~ 80	800 (640)*)
^{116}Cd	7.49	~ 180	1800 (1440)*)
^{130}Te	34.08	~ 20	200 (160)*)
^{136}Xe	8.87	$\sim 5-10$	50-100 (40-80)*)
$^{150}\text{Nd} (?)$	5.6	> 200	> 2000

is ~ 40 tons per year. To collect 10 t of ^{136}Xe one will need 100 t of natural Xe. It means that it will be very difficult (if possible) to have 10 t of ^{136}Xe . But to reach 3 meV sensitivity region one will need $\sim 20-30$ t of ^{136}Xe (see Table 6).

CONCLUSION

Taking into account all above arguments one can conclude;

- 1) 10 t detector with sensitivity to neutrino mass on the level $\sim 3-5$ meV can be created using existing techniques.
- 2) Strong international collaboration will be needed.
- 3) Minimal cost of such experiment is $\sim 100-300$ Mln. dollars.
- 4) $^{130}\text{TeO}_2$ low temperature bolometer looks as the best candidate for such experiments. In this case even natural Te can be used.
- 5) ^{136}Xe is good candidate too (EXO or NEXT type detectors) if it will be possible to produce 20-30 t of enriched Xe.
- 6) HPGe detector made of enriched Ge and low temperature bolometer containing ^{100}Mo could be used too if it will be possible to decrease cost of enriched Ge and Mo production.

In any case, we have to wait, first, for results with CUORE, MAJORANA/GERDA, EXO and other experiments to be sure that all mentioned above problems can be solved. And, of course, new ideas are needed.

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